DTU Library

Wind and wake models for IEC 61400-1 site assessment

Nielsen, Morten; Ejsing Jørgensen, Hans; Frandsen, Sten Tronæs

Published in:
EWEC 2009 Proceedings online

Publication date:
2009

Document Version
Publisher's PDF, also known as Version of record

Wind and wake models for IEC 61400-1 site assessment

Morten Nielsen*, Hans E. Jørgensen† and Sten T. Frandsen‡
Risø DTU, National Laboratory of Sustainable Energy
Wind Energy Division, P.O Box 49, Roskilde DK-4000, Denmark

Abstract

The success of a wind-energy project depends on the wind resource, the wind-farm layout, and the selected turbine type. The aim of the IEC61400-1 standard is to promote safe turbine deployment by a turbine classification system and a protocol for site assessment. This paper discusses the calculations needed for the IEC site assessment. We will develop the wake model in Annex D of the standard for irregular turbine arrays and include effects of wind-sector management.

1 Introduction

The International Electrotechnical Commission provides standards for all kinds of electrical equipment, and among these is the IEC 61400-1 standard for wind turbine safety [1, 2]. The approach is first to classify turbines into well-defined turbine types and then, for specific projects, to verify that site-specific conditions are within the limits of the relevant turbine type. Turbine classification is the responsibility of manufactures and site assessment is the responsibility of project developers.

To achieve a turbine type certificate the turbine must be proofed safe for a range of pre-defined load cases. These load cases are specified by combinations of mode of operation, load type, wind conditions, and partial safety factor. Load types involve both ultimate and fatigue loads accumulated over a design lifetime of twenty years. Wind conditions for this purpose are specified by simple models, which all are scaled by the hub height, a reference wind speed and a reference turbulence intensity. The reference wind is the extreme wind with fifty year recurrence. The turbulence intensity (TI) is defined over ten-minute periods and will have both random variation and wind-speed dependence. In IEC 61400-1 Ed. 2 the TI design level is called characteristic TI and defined as mean plus the standard deviation. Edition 3 operates with the 90% level of the distribution, which is called the representative TI.

For site assessment it must be verified that actual site conditions are less severe than assumed in the turbine certificate. The following criteria applies:

- The 50-year extreme wind must be lower than the reference wind for the turbine type;
- Flow-line inclination at hub height must be within $\pm 8°$ for all wind directions;
- The average wind-shear exponent at hub height α must be positive but less than 0.2. The reason to avoid excessive shear is enhanced fatigue damage and the reason to avoid negative shear is risk of blade-tower interaction;
- The wind-speed distribution must be lower than assumed in the turbine certificate in a range from 0.2 to 0.4 times the reference wind. More exposure in this wind-speed range would enhance fatigue damage;
- The effective TI, see below, must be lower than the applicable IEC model in a range from 0.6 times the rated velocity to the cut-out velocity. The applicable model is either characteristic TI or representative TI depending on whether the turbine type certificate is issued according to edition 2 or 3.

These criteria apply to individual turbine sites. An additional rule states that turbulence must be scaled by a safety factor if the terrain is complex and TI has not been measured. The reason is that in complex terrain the turbulent energy is redistributed among the three velocity components. Terrain complexity is evaluated by criteria based on terrain slopes in the area around each turbine site.

2 Flow modelling

WAsP Engineering uses the LINCOM flow model for prediction of wind shear and flow-line inclination at turbine sites [3, 4]. The flow is calculated as linear perturbations to the vertical wind profile. One set of

*morten.nielsen@risoe.dk
†hans.e.joergensen@risoe.dk
‡stfr@risoe.dtu.dk

perturbations are induced by terrain elevation and the other by variations in surface roughness. Wind-speed dependent surface roughness over water is modelled by a modified version of Charnock's relation, which takes the upwind wind fetch at offshore sites into account. The accuracy of the predicted flow-line inclination has been improved by the use of a terrain following coordinate system. The use of linear equations allows fast solution by Fast Fourier Transforms. This is convenient because we need results for a range of wind directions for to do a site assessment.

LINCOM does not predict accurate turbulence, but the calculated flow field and its velocity gradients are used to predict site-specific modifications of the turbulence structure. This is done by the Mann model [5], which predicts local turbulence from upwind flow deformation by wind shear and terrain effects and gradual adaption to new equilibrium turbulence conditions after changes in surface roughness.

A limitation of WAsP Engineering is that neither LINCOM nor the Mann turbulence model accounts for effects of atmospheric stability or flow systems driven by temperature differences. Furthermore, the neglect of non-linear terms will lead to model errors in terrain with slopes exceeding 25%, as flow separation is likely to develop over such topography.

3 Effective turbulence intensity

Frandsen [6] defines effective turbulence intensity (TI) as the constant TI, which results in the same fatigue-load damage as variable TI from different directions. For at material with Wöhler exponent m, this is modelled as

$$I_{\text{eff}}(u) = \left[\frac{1}{2\pi}\int_0^{2\pi} p\left(\theta\,|u\right) I^m(u,\theta)d\theta\right]^m \quad (1)$$

The implicit assumption is that structural load ranges essentially are linear proportional to TI. According to IEC 61400-1 it is optional to use probability weighting in equation 1, but we generally do so. For this purpose we need the site-specific wind-direction distribution at wind speed u, and this can evaluated by the predicted mean wind climate of WAsP [7]. This mean wind climate is parameterized as sector-wise Weibull distributions with scale and shape parameter A_j and k_j and frequency of occurrence f_j. The wind direction θ determines the sector index j.

$$\begin{aligned} p\left(\theta\,|u\right) &= \frac{p\left(u\,|\theta\right)p\left(\theta\right)}{p\left(u\right)} \\ &= \frac{p\left(u\,|A_j,k_j\right)f_j}{\sum_{i=0}^{N-1} p\left(u\,|A_i,k_i\right)f_i} \end{aligned} \quad (2)$$

Frandsen [6] also suggested a wake turbulence model which IEC 61400-1 Ed.3 adopts in a slightly modified form.

$$I^2_{\text{wake}} = I^2_{\text{ambient}} + I^2_{\text{add}} \quad (3)$$

with

$$I^2_{\text{add}} = \begin{cases} \frac{1}{\left(1.5+0.8\Delta x/d\sqrt{C_T(u)}\right)^2} & \text{(Frandsen)} \\ \frac{0.9}{\left(1.5+0.3\Delta x/d\sqrt{1/u}\right)^2} & \text{(IEC)} \end{cases}$$

Here, d is distance normalized by rotor diameter and $C_T(u)$ is the turbine thrust coefficient. For calculation of effective TI, it was found sufficient to apply a uniform turbulence distribution within the wake and a fixed wake exposure angle of $21.6°$. Multiple wakes did not enhance the turbulence above the level for a single wake.

IEC 61400-1 Ed. 3 Annex D contains a convenient formula for effective TI in regular turbine arrays. Our Windfarm Assessment Tool (WAT) make similar calculations for irregular arrays having variable separation and bearing to neighbour turbines. All wakes have similar exposure angle, but the ones from neighbour turbines may partially cover wakes from more distant turbines, see figure 1. Wake centre angles are approximately equal to bearings of sheltering turbines, however with a small correction accounting for possible wake deflection in non-uniform flow, e.g. over complex terrain. For convenience we do not use the complete flow field for this, but estimate the deflection angle as half the difference in modelled flow directions at wake-producing and sheltered turbines. This is similar to postulating that wake centerlines follow circle segments. The approximation is less plausible for distant turbines but added wake turbulence from these will be of minor importance.

A practical way to program directional turbulence distribution is to subdivide the compass circle into small sectors, say $1°$ wide. A table of TI for these sub-sectors is then filled with background turbulence intensities and repeatedly overwritten with wake turbulence intensities starting with wakes from distant turbines before closer ones. According to equation 3 the added wake turbulence depends on the wind speed at the wake producing turbine, and this may differ from the local wind speed. This wind speed difference is estimated by combination of the ratio of flow-model speed-up factors and wake velocity deficits.

4 Wake velocity deficit

We estimate wake velocity deficits by the wake model of WAsP. This is based on linear wake expansion and a momentum balance in uniform flow.

$$\Delta u_1/u_1 = \left(1-\sqrt{1-C_T(u_0)}\right)\frac{A_{0,\text{rotor}}}{A_{1,\text{wake}}}\frac{A_{1,\text{overlap}}}{A_{1,\text{rotor}}} \quad (4)$$

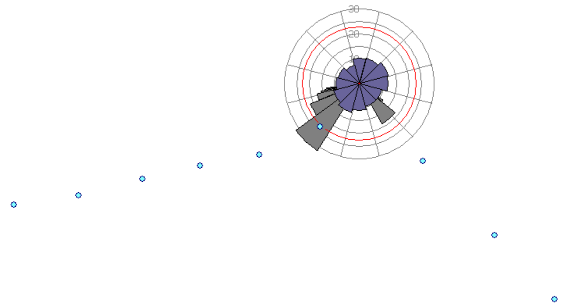

Figure 1: Illustration of an effective turbulence calculation for a turbine site at the intersection of two irregular turbine rows. Background TI for 30° sectors are shaded purple and 21.6° sectors with added wake turbulence are shaded grey. The red circle indicates effective TI for Wöhler number $m = 6$.

Here u_0 and u_1 are undisturbed hub-height wind speeds at the upwind and downwind turbine sites, respectively; $A_{0,\mathrm{rotor}}$ and $A_{1,\mathrm{rotor}}$ are the rotor-swept areas; $A_{1,\mathrm{wake}} = 2\pi\left(D_0 + 2k\Delta x\right)^2$ is the area of the expanded wake at the downwind position with the wake decay factor typically set to $k = 0.075$; $A_{1,\mathrm{overlap}}$ is the overlap area of the expanded wake and the exposed rotor, which is calculated by circle geometry; and, finally, Δu_1 is the resulting velocity deficit at the downwind turbine site. In WAsP the denominator on the left-hand side of equation 4 would be u_0 because the wake model originally was formulated for flat terrain. Here, we use u_1 assuming that wake velocities will speed up proportionally to the background flow. The combined velocity deficits of multiple wakes is not determined by a momentum budget but empirically set to the square root of the sum of squares of individual contributions. For multiple wakes we use corrected velocities when looking up trust coefficients $C_T(u)$. Velocity deficits for upwind turbines are therefore calculated before downwind ones. After some distance the ground will limit vertical expansion and this effect is modelled by imaginary mirror wakes under the terrain. Wake centerlines are assumed to follow the terrain.

5 Turbulence for site assessment

The calculation of effective TI is repeated for a range of wind speeds and compared to the IEC 61400-1 design curve corresponding to the turbulence category declared in the turbine type certificate. It is important to check which edition of the standard the turbine type certificate refers to, as we must use slightly different models, i.e. characteristic TI for edition 2 and representative TI for edition 3. The plot at the top of Figure 2 shows this comparisons. Note that the effective TI suddenly drops at the cut-out wind velocity because upwind turbines are shut down at this limit and produce no wakes. The standard has one further rule stating that the comparison is only necessary in a wind-speed range from 60% of rated wind speed, the lowest wind where rated production is achieved, to the cut-out wind speed. The reason why the calculated TI is much too high in our imaginary example is that turbines are much too close to each other.

WAsP Engineering only predicts neutral-stability TI whereas IEC 61400-1 Ed. 3 asks for the 90% percentile of all situations, a quantity highly influenced by stability effects. We currently handle this lack of information simply by taking the IEC wind-speed dependence with an offset which will match the WEng TI predictions at very high winds. We have a growing concern that this correction is much too conservative, as it adds 33% to the background TI even for a mean wind speed of 15 m/s, which generally is believed to be close to neutral conditions. Too high background TI is mostly a problem for project with large turbine separation, as the wake TI is of relatively small importance. We need to investigate this problem further.

6 Shut-down rules

For some wind-farm layouts, like a single row of turbines on a ridge, operation in the wake of neighbour turbines may be rare, and it is tempting to reduce turbine separations as the loss of power production will be modest. Unfortunately, fatigue-damage of materials like glass fibre is sensitive even to rare occasions of severe turbulence. Although not yet sanctioned by the IEC, it has been suggested to minimize the effects of wake turbulence by shutting down selected turbines during special wind conditions. People has referred to this strategy as wind-sector management, array management, or curtailment.

A simple model for the effect of this kind of turbine operation is is to define turbine shut-down rules excluding selected wind-speed ranges in certain wind direction sectors. The model involves the following aspects:

- Fatigue loads on a shut-down turbine will be very small, so we ignore the integrant in equation 1 when a turbine is out of operation;
- When neighbour turbines are shut down, they contribute no added TI for equation 3 but there might be added TI from more distant turbines. A practical way to program this is by a table of TI in sub-sectors, which iteratively is overwritten with contributions from operating turbines sorted after decreasing distance, see section 3.
- The added TI in equation 3 involves wind speed at the *upwind* turbines site which may differ from the local wind speed. We correct for this by the ratio of flow-model speed-up factors and by

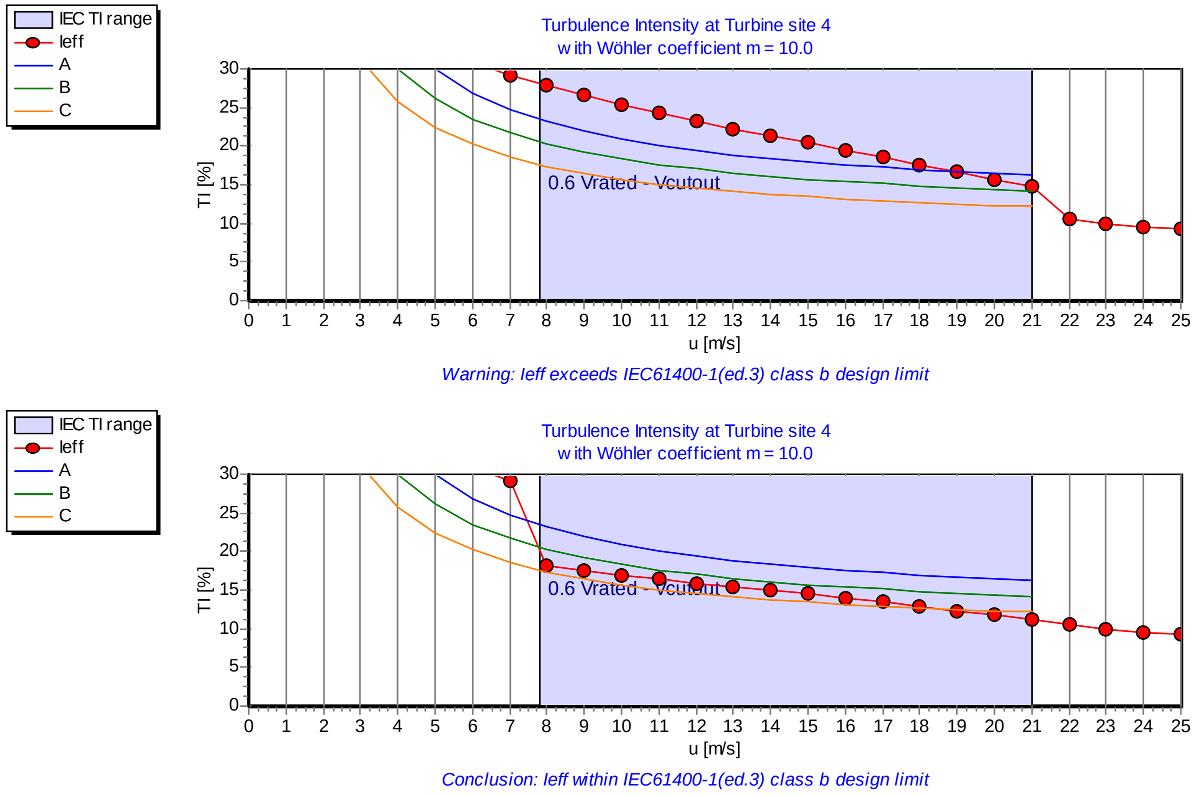

Figure 2: Example of wind-speed dependent effective TI (dots) and IEC design references a) under normal operation and b) with turbine shut-down rules.

the upwind wake velocity deficit. There will, however, be no velocity deficit contributions, see equation 4, for shut-down turbines.

The two plots in figure 2 shows effective TI calculated with and without turbine shut-down rules. The strategy is very successful in this imaginary example, where turbines are deployed unusually close with distances of about two rotor diameters.

7 Regulated energy production

It is of interest to estimate the cost of wind sector management in terms of lost production. For this purpose we review the basic formula for accumulated energy production, used in WAsP [7]

$$P = \int_0^\infty P(u)p(u)\,du \tag{5}$$

The power curve $P(u)$ is approximated by piecewise linear variations

$$P(u) = \frac{P_{i+1} - P_i}{u_{i+1} - u_i}(u - u_i) + P_i \qquad \text{for } u_i \le u < u_{i+1} \tag{6}$$

and the wind-speed probability is expressed by sector-wise Weibull distributions. The combination of Weibull probability and linear power variation has an analytical solution and with cancelling terms it leads to the sum

$$P = \sum_{i=0}^{N-1} \Delta_i \left[P(u_{i+1}) - P(u_i)\right] \tag{7}$$

where the Δ_i factor is

$$\Delta_i = \begin{cases} \frac{G_k(\alpha_{i+1}) - G_k(\alpha_i)}{\alpha_{i+1} - \alpha_i} & \text{for } \alpha_{i+1} \neq \alpha_i \\ -\exp\left(-\alpha_i\right) & \text{for } \alpha_{i+1} = \alpha_i \end{cases}$$

using $\alpha_{i,j} = u_i/A_j$ for dimensionless speed and expressing power-curves discontinuities as two records with identical wind speed, $P_{i+1} \neq P_i$ for $\alpha_{i+1} = \alpha_i$. $G_k(\alpha)$ involves the incomplete gamma function.

$$\begin{aligned} G_k(\alpha) &= k^{-1}\Gamma\left(k^{-1}, \alpha^k\right) \\ &= k^{-1} \int_0^{\alpha^k} t^{k^{-1}-1} \mathrm{e}^{-t} dt \end{aligned} \tag{8}$$

Production estimates with corrections from wake effects and turbine shut-down rules could be written

$$\begin{aligned} P = \int_0^{2\pi} \int_0^\infty & \delta(u - \Delta u, \theta) \\ & \cdot P(u - \Delta u) p(u, \theta)\, du\, d\theta \end{aligned} \tag{9}$$

Here we introduce an indicator function $\delta(u, \theta)$ which is either unity or zero for an operating or shut-down turbine. The integration variable is the ambient wind speed u but both power curve and shut-down rules are functions of wind speed corrected for wake velocity deficit $u - \Delta u$. The integration is not much different from usual, as we can use an apparent power curve $P'(u, \theta) = \delta(u, \theta) P(u)$.

In WAsP, the annual energy productions with and without wake losses are called Gross AEP and Net AEP, respectively. In WAT, the annual energy productions with both wake losses and shut-down rules is called Regulated AEP, and it will be lower than the Net AEP for a regulated turbine but sometimes slightly higher unregulated neighbour turbines, as they are exposed less turbulence.

8 Software

The above wake calculations are implemented in our Windfarm Assessment Tool (WAT). WAT input is generated by a WAsP Engneering script, which calculates and reports site-specific wind conditions. This script also calls WAsP for prediction of the mean wind climate so a twin WAsP/WEng license is required. WAT is in itself free and can be downloaded from `www.wasp.dk/products/wat`.

9 Terrain assessment

9.1 Complex-terrain factors

IEC 61400-1 has an additional rule, which we have not discussed sofar. It declares that in complex terrain the standard deviation of the longitudinal TI must be multiplied by a complex-terrain safety factor

$$C_{\mathrm{ct}} = \frac{1}{1.375} \sqrt{1 + \left(\frac{\sigma_2}{\sigma_1}\right)^2 + \left(\frac{\sigma_3}{\sigma_1}\right)^2} \tag{10}$$

The terrain around a turbine site is categorization as complex according to certain rules considering maximum deviations between local terrain elevation and a plane fitted to the terrain around the turbine as well as the slope of that plane. WAT base the complex-terrain assessments on a terrain model dumped from WEng and evaluates C_{ct} by directional turbulence characteristics in the WEng script. In WAT, it is optional whether to apply C_{ct} factors, as it could be argued that this correction is unnecessary because the Mann turbulence model adequately redistribute turbulence energy among the three velocity components.

9.2 Site calibration

On-site measurements are used to document wind farm power performance. This is done by a combination of power data from the tested turbine and wind data from a nearby reference mast. This is described in IEC 61400-12-1[8] and WAT supports some assessments of that standard.

- IEC 61400-12-1 Annex A includes rules for allowable measurements sectors. Wind sectors are excluded if measurements are disturbed at either the tested turbine or the reference mast. Angles of excluded sectors are prescribed by simple formulae. Obstacle geometry is also needed, and for this purpose WAT imports the WAsP obstacle file.
- IEC 61400-12-1 Annex B includes rules for allowable terrain complexity. If the terrain is too complex, a second met mast must be installed at the exact turbine position prior to turbine installation. After sufficient data collection, a statistical correlation between wind speeds at measurement mast and turbine position is established. This correlation is later used to correct wind measurements for the power performance measurements. This method is called site calibration. It implies planning at an early stage and additional field work, but fortunately it is allowed to skip it if the terrain is less complicated than specified in Annex B. The terrain assessment rules are similar to the complex-terrain indication rules in IEC 61400-1, except that for performance measurement, the tested terrain is limited to annular sectors instead of a circle. The terrain fitting method used in WAT is described in the Appendix of the present paper. If terrain rules are exceeded by less than 50% it is allowed to use modelled flow corrections estimated by a flow model, e.g. LINCOM.

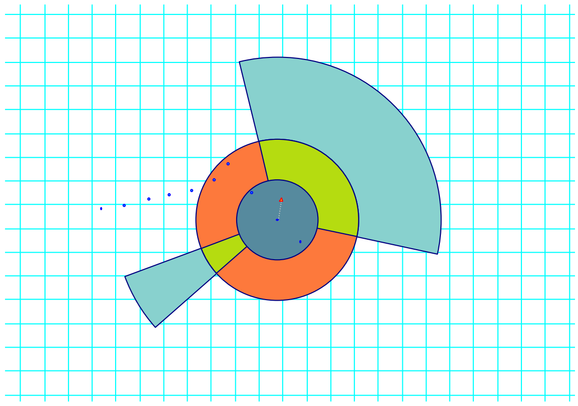

Figure 3: Various sectors for IEC 61400-12-1 terrain assessment

Figure 3 indicates various sectors as defined by turbine layout and mast position according to IEC 61400-12-1 Annex A and B. WAT fits planes to these sectors and determine whether site calibration is needed. The user is allowed to drag the mast around in search for favourable measurement positions.

10 Conclusions

All wind conditions needed for an IEC 61400-1 site assessment can be found by post-processing of flow and turbulence model results followed by some additional wake modelling. We work with WAsP and WAsP Engineering results and implement additional wake calculations in a new program called Windfarm Assessment Tool (WAT). Effects of turbine shut down for turbulence mitigation and some support for planning of an IEC 61400-12-1 site calibration are included. WAT is still under development, and a better match of the neutral-stability TI of WAsP Engineering with the 90% percentile of all turbulence conditions, as required by IEC 61400-1 Ed. 3, is highly desirable. So is possible use of measured turbulence data.

References

[1] IEC 61400-1 Ed. 2, wind turbine safety system - Part 1: Safety requirements, 1999.

[2] IEC 61400-1 Ed. 3, wind turbines - Part 1: Design requirements, 2005.

[3] P. Astrup and S. E. Larsen. WAsP Engineering flow model for wind over land and sea. Technical Report Risø-R-1107(EN), Risø National Laboratory, 1999.

[4] J. Mann, B. H. Jørgensen S. Ott, and H. Frank. WAsP Engineering 2000. Technical Report Risø–R–1356(EN), Risø National Laboratory, 2002.

[5] J. Mann. The spectral velocity tensor in moderately complex terrain. *J. Wind Eng. Ind. Aerodyn.*, 88:153–169, 2000.

[6] S. Frandsen. Turbulence and turbulence-generated fatigue loads in wind turbine clusters. Technical Report Risø-R-1188(EN), Risø National Laboratory, 2007.

[7] N. G. Mortensen, L. Landberg, I. Troen, and E. L. Petersen. Wind atlas analysis and application program (WA$^{\mathrm{S}}$P), vol. 2: User's guide. Technical Report Risø-I-666(EN)(v.2), Risø National Laboratory, 1993.

[8] IEC 61400-12-11, wind turbines - Part 12-1: Power performance measurements of electricity producing wind turbines, 2005. Draft version.

Appendix

IEC 61400-12-1 Annex B makes a terrain assessment in which local terrain deviations in a annular sector is tested from a fitted plane forced through the base the turbine tower z_0. The integral of the squares deviations is

$$\Delta = \int_{\theta_1}^{\theta_2} \int_{r_1}^{r_2} r \left[z(r,\theta) - (z_0 + a \cdot r \sin\theta + b \cdot r \cos\theta) \right]^2 dr\, d\theta \quad (11)$$

where a and b are slopes in x and y directions, and the sector is confined by the angles θ_1 and θ_2 and radii r_1 and r_2. Minimizing Δ with respect to slope gives the solution

$$\begin{bmatrix} a \\ b \end{bmatrix} = \frac{-1}{T^2 - C^2 - S^2} \begin{bmatrix} T+S & -C \\ -C & T-S \end{bmatrix} \begin{bmatrix} D_a \\ D_b \end{bmatrix} \quad (12)$$

using the short-hand notation

$$\begin{aligned} T &= 2\theta_2 - 2\theta_1 \qquad \text{(NB: Angles in [rad] here)} \\ S &= \sin 2\theta_2 - \sin 2\theta_1 \\ C &= \cos 2\theta_2 - \cos 2\theta_1 \\ D_a &= \int_{\theta_1}^{\theta_2} \int_{r_1}^{r_2} \left[z(r,\theta) - z_0 \right] 2r^2 \sin\theta dr\, d\theta \\ D_b &= \int_{\theta_1}^{\theta_2} \int_{r_1}^{r_2} \left[z(r,\theta) - z_0 \right] 2r^2 \cos\theta dr\, d\theta \end{aligned}$$

The integrals D_a and D_b are found numerically. Finally $\max |z_0 + a \cdot r \sin\theta + b \cdot r \cos\theta - z(r,\theta)|$ within the annular sector is determined.